Photon-Noise Limited Direct Detector Based on Disorder-Controlled Electron Heating

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We present a new concept for a hot-electron direct detector (HEDD) capable of counting single millimeter-wave photons. The detector is based on a transition edge sensor (1-μm-size bridge) made from a disordered superconducting film. The electron-phonon coupling at temperatures 100-300 mK is proportional to the elastic electron mean free path l and can be reduced by over an order of magnitude by decreasing l. The microbridge contacts are made from a superconductor with a high critical temperature (Nb) which blocks the thermal diffusion of hot carriers into the contacts. The low electron-phonon heat conductance and the high thermal resistance of the contacts determine the noise equivalent power of ~ 10^{-20}-10^{-21} W/√Hz at 100 mK which is 10^2 to 10^3 times better than that of state-of-the-art bolometers. Due to the effect of disorder, the electron cooling time is ~ 10^{-1}-10^{-2} s at 0.1 K. By exploiting a negative electro-thermal feedback, the detector time constant can be made as short as 10^{-3}-10^{-4} s without sacrificing sensitivity.

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Future millimeter and submillimeter radioastronomy missions will require significant improvement of the sensitivity of radiation detectors. Use of the space interferometers/telescope with cryogenically cooled mirrors will reduce the background-limited noise-equivalent power (*NEP*) down to 10^{-19} W/√Hz [1] even for low-resolution spectral instruments. Bolometers are the most promising candidates to meet these future needs. Currently, state-of-the-art (SOA) bolometers provide an *NEP* of 2×10^{-18} W/√Hz at 0.1 K along with a 60 ms time constant [2].

We propose an alternative way to achieve even higher sensitivity using a voltage-biased hot-electron transition-edge sensor (TES) with properly engineered material properties.

The sensitivity limit of such hot-electron direct detector (HEDD) is limited by thermodynamic fluctuations of the electron temperature, T_e, and the corresponding *NEP* is:

$$NEP = \sqrt{4k_B T_e^2 G_{e-ph}} = \sqrt{4k_B T_e^3 \gamma V / \tau_{e-ph}}\,, \qquad (1)$$

where $G_{e-ph} = C_e/\tau_{e-ph}$ is the effective thermal conductance for the heat transfer between electrons and phonons, and $C_e = \gamma T_e V$ is the electron heat capacity, γ is the Sommerfeld constant, V is the film volume, τ_{e-ph} is the electron-phonon relaxation time. In contrast to the case of conventional bolometers, where the thermal conductance depends on the mechanical design of the bolometer suspension, the *NEP* of an HEDD depends on volume, which can be made very small.

The hot-electron detector may be viewed as the limiting case of a conventional bolometer when the thermal electron-phonon conductance is much lower than the conductance between the film and the environment (that is, the phonon escape from the film to the substrate is faster than the phonon scattering rate from electrons in the film). At subkelvin temperatures this condition is easy to achieve. For 10-30 nm thick films, the phonon escape time is < 1 ns and the phonon-electron scattering time is longer than 1 μs.

It is common to characterize the performance of bolometers by the figure-of-merit $NEP\sqrt{\tau}$ which is roughly the minimum energy that can be detected by a bolometer. In the case of the HEDD, this figure depends only on the specific heat of the electrons, whereas for conventional bolometers there is an additional large contribution due to the specific heat of phonons in the whole detector (the absorber, the thermal link, and the thermometer). Thus, in principle, the hot-electron detectors offer the maximum possible sensitivity of any type of bolometer with the *same* time constant.

It follows from Eq. 1 that to decrease the *NEP*, one should reduce the operating temperature, increase τ_{e-ph} and decrease the electron heat capacity. These quantities are interrelated and we will discuss these issues in detail.

The most sensitive bolometers currently operate at temperatures down to 0.1 K and the required cryogenic coolers are available for space borne applications. This should be the target figure for HEDD optimization. It is also advantageous to operate an HEDD at 0.3 K (much simpler coolers) with the sensitivity still exceeding that of SOA bolometers.

The electron-phonon relaxation time in metals is proportional T^{-n} ($n \approx 3$ for clean metals). Typically, $\tau_{e-ph} \approx 10^{-5}$-$10^{-4}$ s at 0.1 K. This speed is excessively high (at the expense of sensitivity) for many of applications (a 1 ms response time is often sufficient). If a high speed is required, it can be achieved by exploiting the negative electro-thermal feedback (ETF) [3] in a TES which effectively reduces the response time by factor of ~100. The *NEP* of a bolometer is not affected by the ETF [4]. Therefore for a hot-electron TES, one can attain *both sensitive and fast* performance in two steps: first, *increasing* the intrinsic electron-phonon time (≡ increasing the sensitivity) by adjusting the disorder in the film (see discussion below), and, second, *decreasing* the response time again by employing negative ETF. This is not readily possible in a normal metal counterpart device [5] which uses an SIN tunnel junction to read out the electron temperature change in a normal metal absorber caused by radiation.

The electron-phonon interaction in impure metals strongly depends on the electron-impurity (or electron-boundary) scattering rate (see [6,7]) which can be used as a tool to adjust τ_{e-ph}. A number of scattering processes (including electron scattering by vibrating impurities and diffusion enhanced electron-phonon scattering) interfere, giving a non-trivial dependence of τ_{e-ph} on the electron mean free path. The crucial parameter driving τ_{e-ph} is ql ($q = k_BT/\hbar u$ is the phonon wavevector, u is the sound velocity). At subkelvin temperatures, $ql \ll 1$ even in clean thin films because of the diffusive scattering of electrons at the film surface. In this case [8]:

$$\tau_{e-ph}^{-1} = 2.7\pi^4 \beta_t \left(\frac{k_B T}{\hbar}\right)^4 \frac{k_F l}{(k_F u_t)^3}. \qquad (2)$$

Here β_t is the dimensionless interaction constant between electrons and transverse phonons, k_F is the Fermi wavevector, and u_t is the sound velocity for transverse phonons.

Some predictions of theory [8] are shown in Fig. 1 (more detailed comparison between the theory and experiments for other materials can be found in [6,9,10]). The control over the electron mean free path can be achieved by making films thinner or/and by irradiating films with high-energy ions [9].

Equation 2 was derived assuming a 3D phonon spectrum. Since in thin films at ultralow temperature $qd < 1$ (d is the film thickness), the phonon spectrum may modify. In this case the relaxation rate will be driven by an exponential factor, $\exp(-1/qd)$ [11], which decreases the relaxation speed even more comparing to the 3D case of Eq. 2.

A practical implementation of the hot-electron mechanism at subkelvin temperatures requires special design of the contact areas (Fig. 2). The leads should be made from a superconductor with a higher critical temperature than that of the bridge material. A large superconducting gap in the contacts, Δ, creates an energy barrier for the leakage of the hot electrons energy from the detector. The dc bias and rf currents will flow freely through the structure, whereas the outdiffusion of hot electrons with energies $\varepsilon < \Delta$ will be blocked by Andreev reflection. It follows from Eq. 1 that the *NEP* decreases with decreasing length of the microbridge. On the other hand, there is a limit for the length reduction which is imposed by two effects. First, the length of the HEDD should be larger than the coherence length in the normal metal, $L_T=(hD/4\pi^2k_BT)^{1/2}$, otherwise the difference between the critical temperatures of the detector and the superconducting leads will be washed out because of to the proximity effect. At $T \approx 0.1$ K and $D \approx 2$ cm^2/s this imposes a limit on the device length $L >> 2L_T = 100$ nm. Second, if the length is too small, the hot quasiparticles with energies greater than Δ can escape from the detector before thermalization. The escape of the non-thermalized electrons would reduce the quantum efficiency of the detector at frequencies $\nu > \Delta/h$ (e.g., for Nb Δ/h corresponds to 360 GHz). One way of preventing deterioration of the spectral response at high frequencies is to make the length of the detector greater than the electron diffusion length at the edge of the gap $l_{e-e} = [D\tau_{e-e}(\Delta_{Nb})]^{1/2}$. Taking $\tau_{e-e}(\Delta) \approx 10^{-11}$ s we estimate this length to be of ~ 90 nm. If the bridge length is ≈ 1 μm these difficulties can be safely avoided.

Typical impure superconducting films will still demonstrate good superconducting properties if the thickness is ≥ 10 nm. In this case, the bridge width, w, is defined by the requirement that the normal resistance, R_n, should be 50-100 Ω to match the device with a planar antenna. For many materials this corresponds to a one square area bridge (ie: 1×1 μm^2 for 0.1 K). The lateral size can be slightly reduced (by 1.5-2 times) if the detector works at 0.3 K (both L_T and $l_{e-e} \sim T^{1/2}$).

As an example of the HEDD performance, we calculated the characteristics of a W sensor. Although the theory predicts the electron-phonon time as long as 13 ms at 0.1 K, we took for our model a much more conservative value: τ_{e-ph} = 1 ms. This is close to what a recent experiment [12] suggests (0.36 ms) for presumably clean W at 80 mK. With T_c = 80 mK and T = 40 mK (as in Ref. 12) and δT_c = 2 mK, we solved the heat balance equation for the electron temperature:

$$AV\left(T_e^6 - T^6\right) = V_b^2 / R(T_e). \tag{2}$$

Here $A = \gamma / \left[6\tau_{e-ph}(T_c)T_c^4\right]$, V_b is the bias voltage. The $R(T_e)$ dependence was modeled by a smooth function providing $dR/dT_{|T=T_c} = R_n/\delta T_c$. Then the current-voltage characteristic, the self-heating parameter (sometimes called the ETF loop gain) $C = (V_b/R)^2(dR/dT)G_{e-ph}^{-1}$, the current responsivity, $S_I = (1/V_b)C/(C+1)$ and the NEP were calculated. Besides the contribution of the electron temperature fluctuation given by Eq. 1 with $G_{e-ph} = 3.8\times10^{-17}$ W/K, the total NEP includes the SQUID amplifier contribution, $NEP_{SQUID} = i_n/S_I$ (SQUID noise $i_n \approx 1$ pA/$\sqrt{\text{Hz}}$ [13]) and the Johnson noise [14] of the superconductor-normal-superconductor SNS system, $NEP_J = (4k_BT_eV_b^2/R)^{1/2}/C$ [4]. The results of the modeling are summarized in Fig. 3.

As one can see, in order to make the electron temperature fluctuations the dominating noise mechanism, the device should operate at low bias voltages < 4 nV. The self-heating parameter is large in this case (up to 60). Then the actual device speed will be $\tau = \tau_{e-ph}/(C+1) \approx 44$ μs, and the energy resolution $NEP\sqrt{\tau}$ will be $\approx 2.4\times10^{-23}$ J which corresponds to a ~ 40 GHz photon energy. This sensitivity exceeds that expected from the other detector concepts: a submillimeter wave photometer consisting of a superconducting absorber and a single-electron transistor [15], and a normal metal hot-electron bolometer [5].

Other materials with critical temperature around 0.1 K (e.g., Hf) or around 0.3 K (Ti and normal-superconductor proximity bi-layers Ti/Al, Cu/Al or Au/Mo with adjustable T_c [16]) can also be used to fabricate HEDDs. The electron-phonon relaxation time in these systems is not known yet. The theory predictions for metal components of these bi-layers are given in Table I. For the 0.3 K operation, the *NEP* can be less than 10^{-18} W/√Hz. This figure is better than that for the SAO bolometers operated at 0.1 K.

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Table I. The NEP due to electron temperature fluctuations and the electron phonon time in HEDDs made from impure metals.

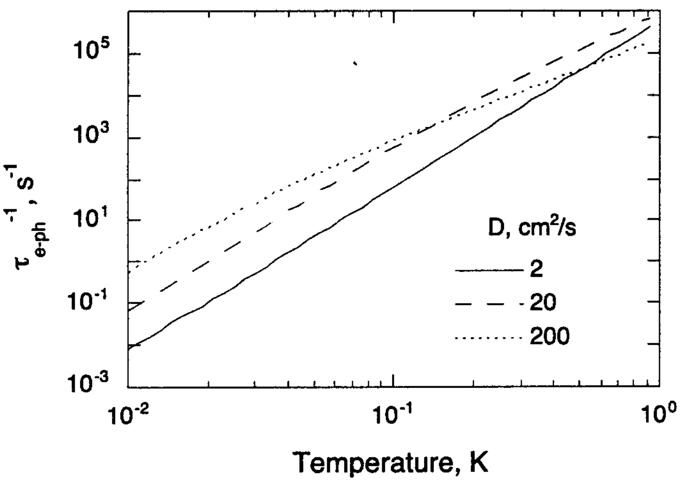
Material	T = 0.1 K		T = 0.3 K	
	NEP, W/√Hz	$\tau_{e\text{-}ph}$, ms	NEP, W/√Hz	$\tau_{e\text{-}ph}$, μs
Al	6.6×10^{-21}	1.7	6.6×10^{-19}	20
Cu	9.0×10^{-21}	0.7	4.3×10^{-19}	8.0
Au	18×10^{-21}	0.1	9.0×10^{-19}	1.3
Ti			8.0×10^{-19}	7.3
W	2.4×10^{-21}	13		
Hf	9.9×10^{-21}	0.9		

Figure Captions.

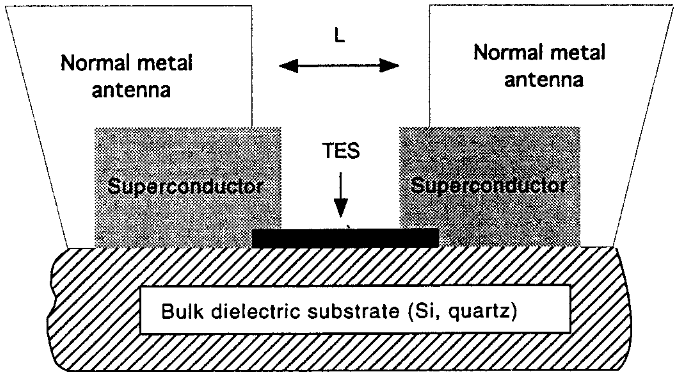
Fig. 1. The theory prediction for the electron-phonon relaxation rate, $\tau_{e\text{-}ph}^{-1}$, in W.

Fig. 2. Schematic diagram of the HEDD design. The TES is surrounded by superconducting "Andreev mirrors" which prevent the leakage of the thermal energy into the contacts. The energy gap in the TES is suppressed while in the contacts it is fully open. The size of superconducting contacts is small to avoid undesirable rf loss at high frequencies.

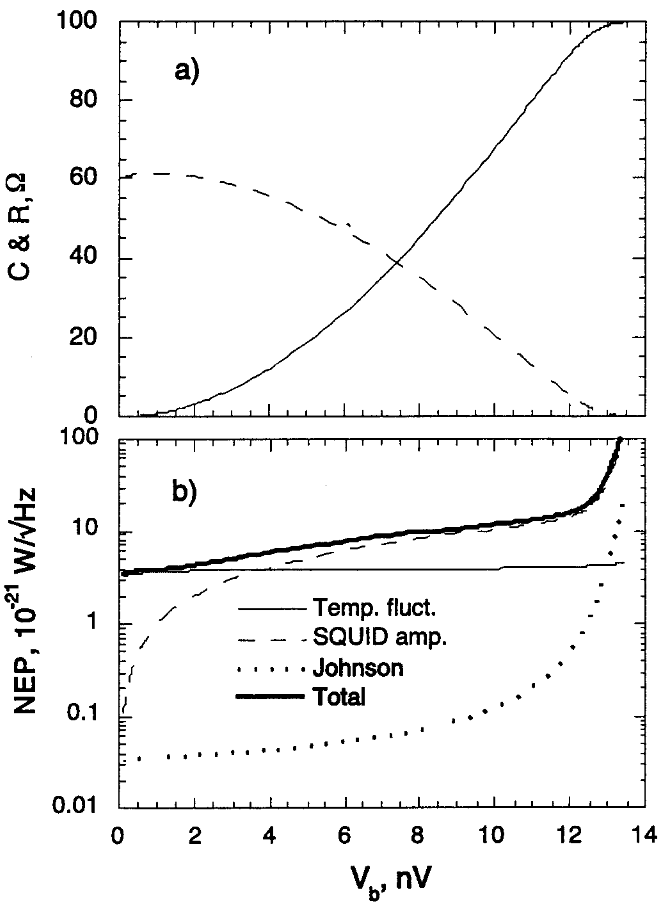
Fig. 3. Results of the computer modeling of the HEDD characteristics. a) The detector resistance, R, and the self-heating parameter, C, vs bias volatge V_b. b) Contributions of the various noise sources in the total detector noise. The detector should operate at low bias voltages (<4 nV) to allow for high self-heating parameter value. In this case, the temperature fluctuation noise dominates and the total NEP is minimal.



B.Karasik et al. APL, Fig. 1



B.Karasik et al. APL, Fig. 2.



B.Karasik et al. APL, Fig. 3.